NLO corrections using the Monte Carlo MCFM

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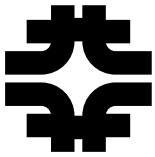


In collaboration with:
R. K. Ellis

NLO QCD Simulations

- Single top production
  - Fully differential final states - see Z. Sullivan's talk
    Harris, Laenen, Phaf, Sullivan and Weinzierl, 2000
- Diboson production, e.g. $p\bar{p} \to W^+W^- \to$ leptons.
  - Baur et al. - lepton correlations only partially included
    Ohnemus, 1994
    Baur, Han and Ohnemus, 1995, 1996
  - Dixon et al. - full correlations, anomalous couplings
    Dixon, Kunszt and Signer, 1999
  - MCFM - full correlations, singly-resonant contributions
    JC and Ellis, 1999
- Inclusive jets
  - JETRAD - 1 and 2 jets only
    Giele, Glover and Kosower, 1993
  - Giele, Kilgore - 3 jet production
    Giele, Kilgore, 2000

NLO QCD Simulations

- Drell-Yan + heavy flavours
  - MCFM - $W^{\pm}g^{\star}(\rightarrow b\bar{b})$
    Ellis and Veseli, 1998
  - MCFM - $Zg^{\star}(\rightarrow b\bar{b})$
    JC and Ellis, 2000
- Drell-Yan + jets
  - DYRAD - handles vector boson + 0 or 1 jets
    Giele, Glover and Kosower, 1993
  - VECBOS - handles vector boson + up to 3 (Z) or 4 (W) jets at leading order only
    Berends, Kuijf, Tausk and Giele, 1991

MCFM Background

- The Tevatron Run II will be sensitive to processes at the femtobarn level.
- Particularly interesting are final states involving heavy quarks, leptons and missing energy.
- MCFM aims to provide a unified description of such processes at NLO accuracy.
- The extension to NLO is made possible in many cases by the recent calculations of virtual matrix elements involving a vector boson and four partons.
- Similar philosophy, but different approach to Pythia. Whilst Pythia has the advantages of extra radiation (partially included in a NLO calculation) and showering, a fixed order MC may be viewed as theoretically cleaner.

MCFM Process List

Included at NLO	
$p\bar{p} \to W^{\pm}/Z$	$p\bar{p} \to W^{+} + W^{-}$
$p\bar{p} \to W^{\pm} + Z$	$p\bar{p} \to Z + Z$
$p\bar{p} \to W^{\pm}/Z + H$	$p\bar{p} \to W^{\pm}/Z + 1$ jet
$p\bar{p} \to W^{\pm}/Z + g^{\star}\,(\to b\bar{b})$	

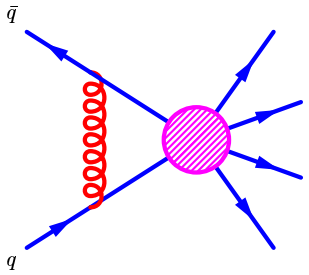
- Various leptonic and/or hadronic decays of the bosons are included as further sub-processes.

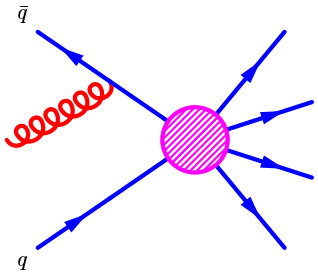
No NLO prediction for W/Z + 2 jets is available, but this is under construction in MCFM.

Monte Carlo Ingredients - 1

- Helicity amplitudes for the virtual and real ME's

m-parton process

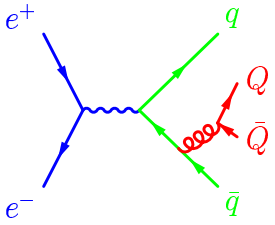


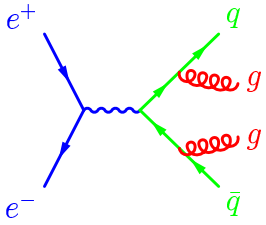


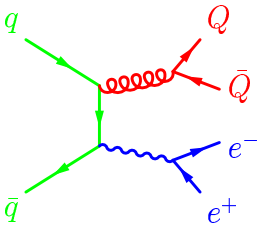
$(m+1)$-parton process

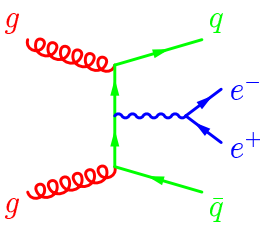
- Many of the NLO matrix elements are obtained by crossing the ones calculated for $e^+e^- \to 4$ jets.

Bern, Dixon, Kosower and Weinzierl, Nucl. Phys. **B489** (1997) 3
Glover and Miller, Phys. Lett. **B396** (1997) 257
Campbell, Glover and Miller, Phys. Lett. **B409** (1997) 503









Monte Carlo Ingredients - 2

- Singular pieces of the real matrix elements must be identified and cancelled by an appropriate set of counter-terms.

- MCFM uses the dipole method to cancel the infrared divergences between real and virtual contributions.

Catani and Seymour, Nucl. Phys. **B485** (1997) 291

$$\sigma_{real}^{m+1} = \int_{(m+1)} (d\sigma_{real} - d\sigma_{counter}) + \int_{(m+1)} d\sigma_{counter}$$

$$= (\text{integrable terms}) + \sum_{dipoles} \int_m d\sigma \otimes \int_1 dV_{dipole}$$

where the 1-dimensional integral over the dipoles leads to soft and collinear divergences (poles in ϵ).

- These poles manifestly multiply m-parton ME's and may be cancelled against poles from the loop diagrams.

Higgs search using MCFM

- Studies using LO Monte Carlos and other event generators show that for a Higgs in the mass range of 100-130 GeV, the most promising channels for discovery at Run II are associated Higgs production.

Stange, Marciano, Willenbrock, Phys. Rev. **D49** (1994) 1354, **D50** (1994) 4491

$$p\bar{p} \longrightarrow W(\rightarrow e\nu)H(\rightarrow b\bar{b})$$
$$p\bar{p} \longrightarrow Z(\rightarrow \nu\bar{\nu}, \ell\bar{\ell})H(\rightarrow b\bar{b})$$

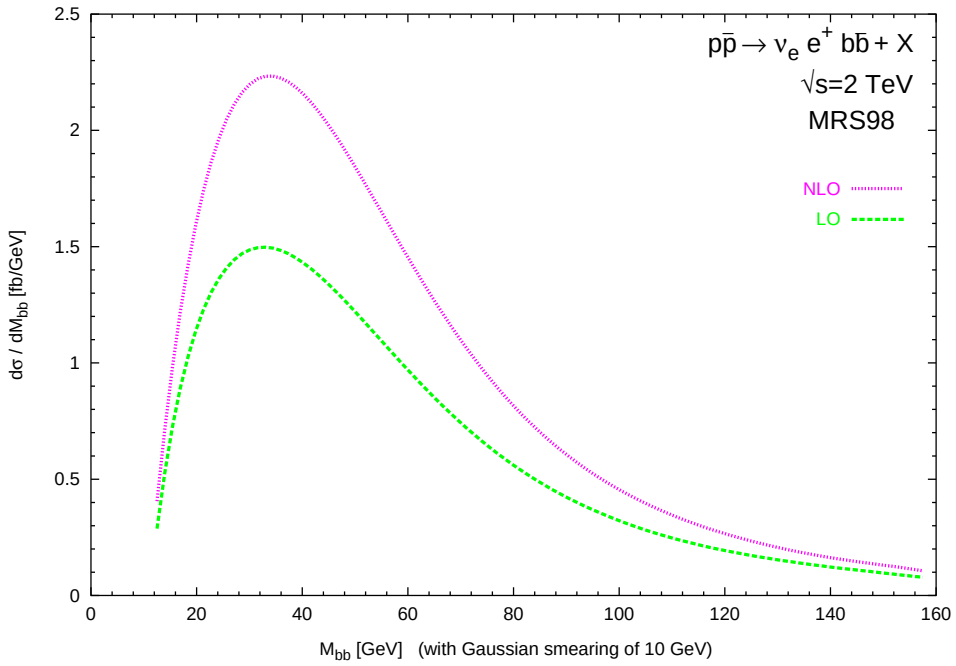
- Particularly interesting in the light of hints from LEP2.
- Backgrounds for the WH signal:

$$p\bar{p} \longrightarrow W\, g^{\star}(\rightarrow b\bar{b})$$
$$p\bar{p} \longrightarrow W\, Z/\gamma^{\star}(\rightarrow b\bar{b})$$

$$p\bar{p} \longrightarrow t(\rightarrow bW^{+})\bar{t}(\rightarrow \bar{b}W^{-})$$
$$p\bar{p} \longrightarrow W^{\pm *}(t(\rightarrow bW^{+})\bar{b})$$
$$qg \longrightarrow q't(\rightarrow bW^{+})\bar{b}$$

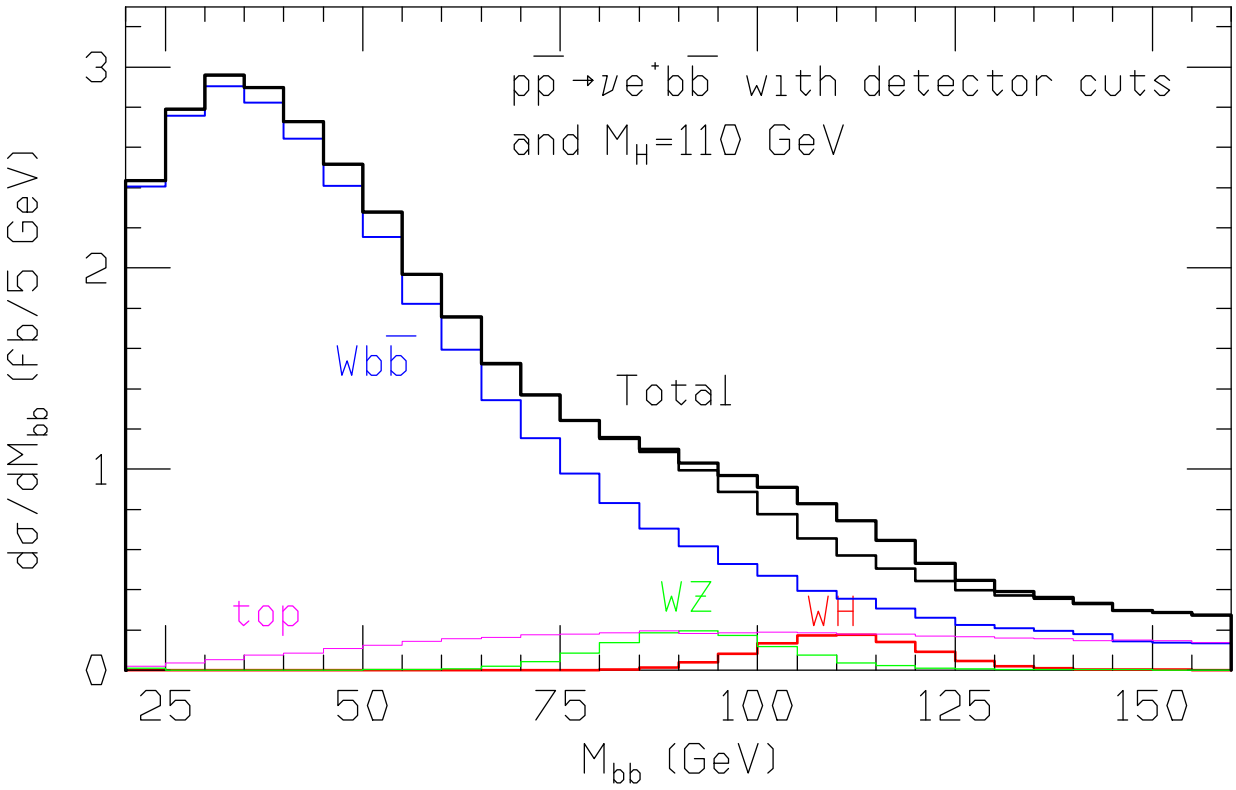
Results for $Wb\bar{b}$

- Use a set of "standard" cuts from the literature, appropriate for the WH study and MRS98 parton distribution functions.
- $m_{b\bar{b}}$ distribution at LO and NLO, scale of 100 GeV.



- The shape changes very little and the K-factor ≈ 1.5

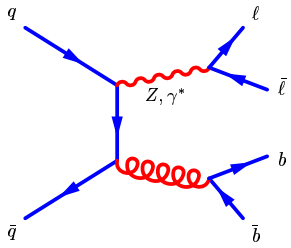
Signal and Backgrounds for $m_H = 110$ GeV



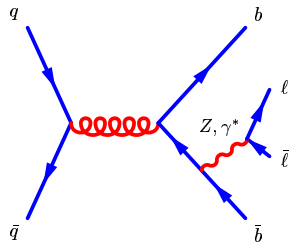
- Double b-tagging efficiency of $\epsilon_{b\bar{b}} = 0.45$
- Extraction of the signal requires detailed knowledge of the normalization and the kinematics of the backgrounds.

Results for $Zb\bar{b}$

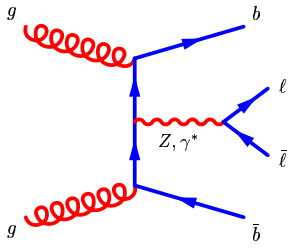
- New results include radiative corrections, relevant for a further Higgs search in the channel ZH.
- The required matrix elements are very similar to the $Wb\bar{b}$ case,



(a)



(b)

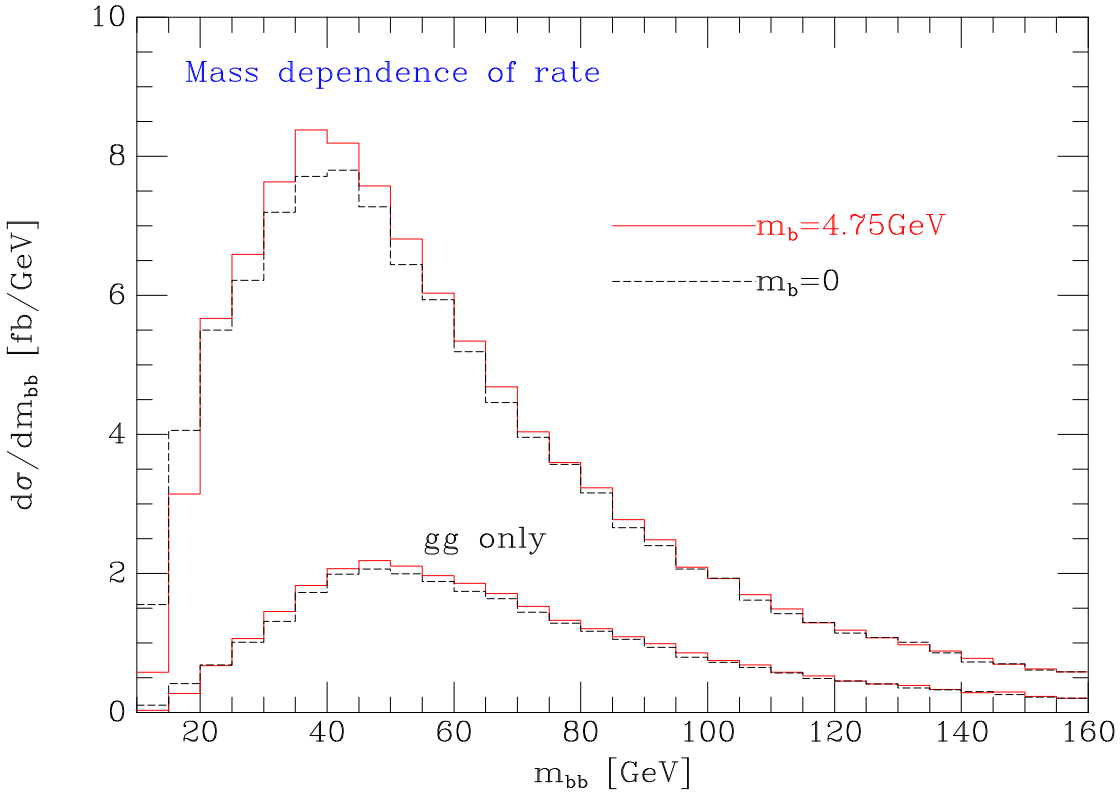


(c)

with additional contributions from gg initial states.

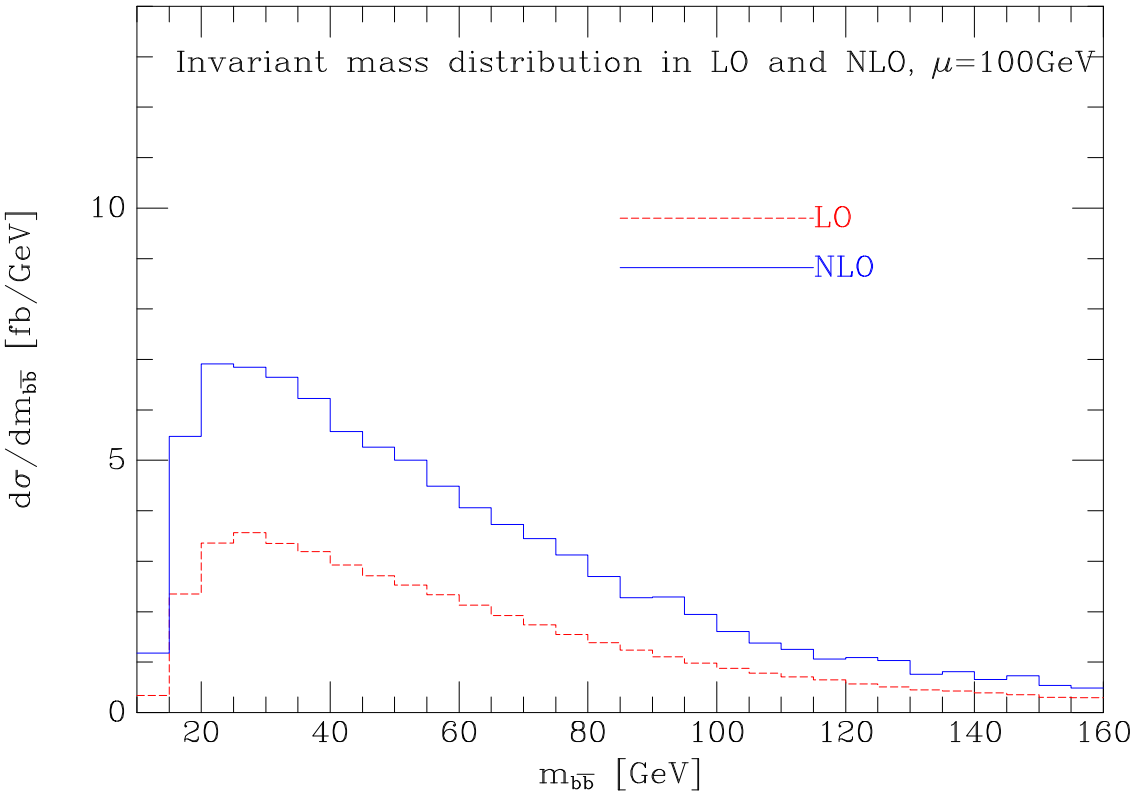
The gg sub-process

• A $b\bar{b}$ pair with a large invariant mass can be produced by the gg initial state process, without off-shell propagators. This gives rise to a large contribution that is important for searches.



$m_{b\bar{b}}$ mass distribution for $Zb\bar{b}$

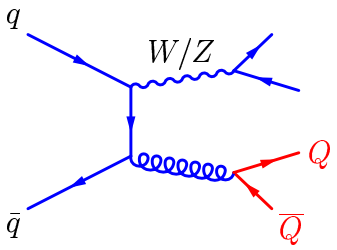
- For a 'conventional' scale of 100 GeV, there is a large K-factor in the region of interest, around 1.8.



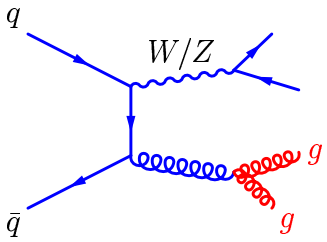
- The entire distribution is changed both in shape and normalization - perhaps suggesting that this scale choice is no longer appropriate ($\rightarrow$ new gg processes).

$W + 2$ jets: work in progress

- View the $W + 2$ jets process as an extension of the $Wb\bar{b}$ and $Zb\bar{b}$ calculations already performed:
  - $Wb\bar{b}$ – part of $q\bar{q} \to W + q'\bar{q}'$



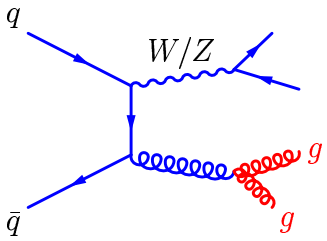
  - $Zb\bar{b}$ – contains $gg \to Z + q\bar{q}$ + crossings



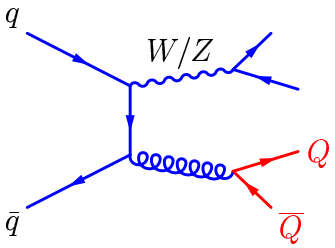
- There are extra parton configurations that we must count.
- The contribution from the diagrams that include real radiation must incorporate the extra singularities due to more configurations of soft/collinear gluons and collinear quark pairs.

$W + 2$ jets at lowest order

- Separate the diagrams by colour structure:

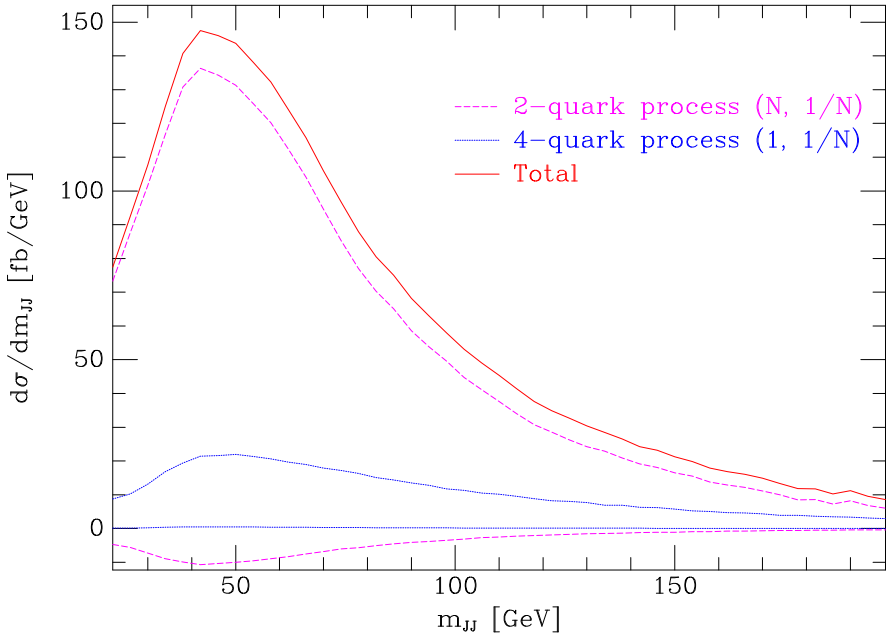


$\propto N, 1/N$



$\propto 1, 1/N \times \delta_{qQ}$

- Typical distribution, standard set of cuts:



$W + 2$ jets: strategy

$$|\mathcal{M}_{NLO}(Vq\bar{q}gg)|^2 \sim \quad 1 \quad \longleftarrow \text{Near completion}$$
$$+\frac{1}{N^2}$$
$$+\frac{1}{N^4}$$

$$|\mathcal{M}_{NLO}(Vq\bar{q}Q\bar{Q})|^2 \sim \quad \frac{1}{N} \quad \longleftarrow \text{Next target}$$
$$+\frac{1}{N^3}$$
$$+\frac{1}{N^2} \times \delta_{qQ}$$
$$+\frac{1}{N^4} \times \delta_{qQ}$$

- Emphasis on $W + 2$ jet first

Conclusions

- Large radiative corrections to the $Wb\bar{b}$ and $Zb\bar{b}$ processes can significantly change estimates of the backgrounds to the processes $p\bar{p} \to WH$ and $p\bar{p} \to ZH$, which will be important search channels at the Tevatron.

- Work is still ongoing in the area of $W/Z + 2$ jet production, for which first results should be available soon.

- MCFM may be downloaded from

`http://www-theory.fnal.gov/people/campbell/mcfm.html`